Photonic Crystal Multi-Core Fibers for Future High-Capacity Transmission Systems

Kazunori MUKASA†a), Katsunori IMAMURA†, Yukihiro TSUCHIDA†, and Ryuich SUGIZAKI†, Members

SUMMARY This paper describes recent developments of photonic crystal fibers (PCFs), which can realize ultra wide-band transmission or large $A_{\text{eff}}$, as well as photonic crystal multi-core fibers (PC-MCFs), which have large potentials as future high-capacity transmission lines using Space Division Multiplexing.

key words: PCF, multi-core fiber, WDM, SDM

1. Introduction

Since the internet traffic is rapidly growing, it is expected that the current transmission fibers will become inadequate in around 2015–2020 [1], [2]. Therefore, some innovations with transmission fibers for future high-capacity transmission have been strongly required. Expanding the transmission bands from the current C and/or L-Band by utilizing new transmission fibers is one interesting direction. For example, photonic crystal fibers (PCFs), which have an endlessly single mode (ESM) property, are one of the interesting candidates to realize ultra wide-band transmissions [3]–[6]. In addition, PCFs, which are designed to realize large effective core area ($A_{\text{eff}}$), have been also investigated and reported [7]–[9]. These reports said that PCFs had a large potential in realizing larger $A_{\text{eff}}$ than conventional solid fibers. For these aspects, PCFs can offer very interesting optical properties as future high-capacity transmission lines.

Recently, another important direction, namely using space division multiplexing (SDM) by using multi-core fibers (MCFs), has been paid considerable attention [10]–[13]. A multi-core fiber literally multiples the core number within a fiber dimension, which enables multiple transmission capacity per one fiber. Naturally, the ultra high-capacity transmission, by combining both ultra wide-band wavelength division multiplexing (WDM) and SDM, can be realized by applying PC-MCFs [10]. In addition, PC-MCFs give another interesting possibility, namely SDM with large $A_{\text{eff}}$ cores [11].

Merits of using PCFs and PC-MCFs compared to conventional fiber types will be demonstrated and discussed in this paper, with some novel R&D results.

2. Photonic Crystal Fibers (Single Core)

2.1 Why Have Photonic Crystal Fibers Become Important? — Properties and Limitations of Conventional Fibers —

Even though many types of transmission fibers, including Non-Zero Dispersion Shifted Fibers (NZ-DSFs) have been developed [14], Standard Single Mode Fibers (SMFs) are far more widely used all over the world. This is because the standard SMFs can provide not only good optical properties, such as low attenuation loss and large $A_{\text{eff}}$, but also an excellent mass-productivity. Optical properties of an SMF and NZ-DSFs are shown in Table 1. Even though NZ-DSFs can provide low dispersion value, SMFs have the low nonlinearity, which is realized by low loss and large $A_{\text{eff}}$. These features have become more important, since multi-level signal formats, which are essential for future higher capacity transmissions, require large $A_{\text{eff}}$ and large dispersion fibers as SMFs [15], [16].

However, the usable transmission band of SMFs is limited to conventional telecom band, which corresponds to 1300–1650 nm. In the future, it will be required to use wider transmission bands [5], [6]. PCFs are of particular interest, since they have unique properties, e.g. the ESM property, which is difficult to be realized by using conventional solid fibers [17]. For example, a new band, namely 1.0-μm band, is recognized as the next-generation band [18], [19]. However, SMFs have a cutoff wavelength (λc) around 1250 nm, and therefore realizing the 1.0-μm band transmission is difficult in the case of SMFs. In addition to that, $A_{\text{eff}}$ of conventional solid SMFs has been limited to around 80 $\mu m^2$. By optimizing index profiles, $A_{\text{eff}}$ has been enlarged, in particular for submarine transmission fibers, but it has been limited to around 110 $\mu m^2$ up until now [20].

Table 1 Typical optical properties of an SMF and NZ-DSFs ($\lambda$=1550 nm).

<table>
<thead>
<tr>
<th></th>
<th>$A_{\text{eff}}$ ($\mu m^2$)</th>
<th>Loss (dB/km)</th>
<th>Dispersion (ps/nm/km)</th>
<th>D Slope (ps/nm$^2$/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMF</td>
<td>80</td>
<td>0.185</td>
<td>16</td>
<td>0.06</td>
</tr>
<tr>
<td>NZ1</td>
<td>72</td>
<td>0.19</td>
<td>4.6</td>
<td>0.09</td>
</tr>
<tr>
<td>NZ2</td>
<td>65</td>
<td>0.19</td>
<td>8</td>
<td>0.06-0.07</td>
</tr>
<tr>
<td>NZ3</td>
<td>55</td>
<td>0.19</td>
<td>4.8</td>
<td>0.04-0.05</td>
</tr>
<tr>
<td>NZ4</td>
<td>45</td>
<td>0.19</td>
<td>4.6</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Manuscript received September 1, 2010.
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DOI: 10.1587/transcom.E94.B.376
2.2 Development of Photonic Crystal Fibers for Ultra Wide-Band Transmission

Firstly, PCFs for ultra wide-band transmissions have been investigated. As described, conventional SMFs have a limitation of $\lambda_c$ (SM-operation region), which is around $\sim 1250$ nm. On the other hand, PCFs have the ESM property, which breaks the limitation caused by the $\lambda_c$. However, since PCFs confine the light by air holes surrounding a silica core, they show quite different properties from conventional solid fibers. A macro-bending loss increase towards both short and long wavelengths is one of them [21], which is interesting but potentially limits the wide-band transmission ability of PCFs. In particular, the short wavelength bend-loss edge practically limits the transmission bands of the PCFs. Therefore, the structure of PCFs needs to be carefully optimized, taking the macro-bending loss property into account. Therefore, we have carefully optimized the structure of PCFs by the Finite Element Method (FEM) to realize as large $A_e$ as possible, keeping the ESM property and low macro-bending loss. Considering the real field deployments, the target macro-bending loss at 1050 nm was set to $<5$ dB/m at 20 mmφ. A structure of PCFs is shown in Fig. 1. Since the PCFs have uniform hole diameters (d) and hole-to-hole pitches ($\Lambda$), the optical properties are determined by $\Lambda$, d/\Lambda, and number of layers of air holes.

At first, d/\Lambda was optimized to satisfy the ESM property. It is known that the large d/\Lambda is advantageous in terms of realizing large $A_{\text{eff}}$ and low macro-bending loss [3]. On the other hand, large d/\Lambda supports higher order modes (HOMs) guidance, and the ESM property can not be realized, if d/\Lambda is too large. We assumed that the ESM property would be obtained, if the V-value at 500 nm is less than 2.405, using an assumption widely used for conventional fibers [22], [23]. The maximum d/\Lambda, which ensures the ESM property, is shown in Fig. 2. We set the d/\Lambda value to 0.43, since the ESM can be obtained as far as $\Lambda < 10 \mu$m.

Then, we optimized the $\Lambda$ value and number of layers taking macro-bending loss as well as confinement loss, which also is an important factor for the design of PCFs [3], into accounts. Examples of simulation results are shown in Fig. 3 and Fig. 4. The target macro-bending loss was set to $<10$ dB/m at 20 mm diameter, and the confinement loss should be ignorable. From the simulation results, we figured out that the optimum profile parameters, to realize 1.0-μm band as well as telecom-band transmission, was d/\Lambda=0.43, $\Lambda=7-8 \mu$m and number of layers of 5-layer.

Based on the simulation results, we have fabricated the PCFs. The obtained optical properties are shown in Table 2. The obtained optical properties are agreed well with the predicted values, which were optimized for realizing the 1.0-μm band transmission. Loss values are not influenced by the
Table 2  Optical properties of fabricated holey fibers.

<table>
<thead>
<tr>
<th></th>
<th>W.L.*</th>
<th>No.1</th>
<th>No.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$ [\mu m]</td>
<td></td>
<td>7.1</td>
<td>8.1</td>
</tr>
<tr>
<td>$d/A$</td>
<td></td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Dispersion [ps/nm/km]</td>
<td>1.55</td>
<td>32.2</td>
<td>30.0</td>
</tr>
<tr>
<td>D. Slope [ps/nm$^2$/km]</td>
<td>1.55</td>
<td>0.071</td>
<td>0.069</td>
</tr>
<tr>
<td>Loss [dB/m]</td>
<td></td>
<td>1.05</td>
<td>0.85</td>
</tr>
<tr>
<td>$A_{\text{eff}}$ [\mu m$^2$]</td>
<td>1.55</td>
<td>67.0</td>
<td>82.6</td>
</tr>
<tr>
<td>$\lambda_c$ [nm]</td>
<td></td>
<td>ESM</td>
<td>ESM</td>
</tr>
<tr>
<td>BL 20$\phi$ [dB/m]</td>
<td>1.55</td>
<td>0.01</td>
<td>0.10</td>
</tr>
</tbody>
</table>

*) Wavelength [\mu m]  
**) Macro-bending loss at 20 mm diameter

*) Wavelength [\mu m]  
**) Macro-bending loss at 20 mm diameter

2.3 Development of Photonic Crystal Fibers for Low Nonlinearity

To realize long-haul high-capacity transmissions, the expansion of $A_{\text{eff}}$ in optical fibers is also strongly demanded [23]. The enlargement of $A_{\text{eff}}$ to 160 $\mu$m$^2$, keeping low macro-bending loss and low $\lambda_c$, was reported by using the W-shaped profile [8]. However, the expansion of $A_{\text{eff}}$, e.g. larger than 110 $\mu$m$^2$, has been limited by the effect of micro-bending loss increase in the real field [20]. In order to overcome the trade-off between large $A_{\text{eff}}$ and low micro-bending loss, we investigated new potentials of using the PCFs.

For the investigation, we selected the PCFs with $A_{\text{eff}}$ of 150 $\mu$m$^2$ at 1550 nm, as well as the SMFs with $A_{\text{eff}}$ of 115 $\mu$m$^2$ and 130 $\mu$m$^2$, as a target. As for the PCFs, we considered the triangular-lattice PCFs as shown in the Fig. 1. Figure 6 shows the relationship between macro-bending losses at 20 mm$\phi$ and $A_{\text{eff}}$ at 1550 nm of PCFs, calculated by the FEM. Each solid curve in Fig. 6 corresponds to different values of $d/A$ (from 0.35 to 0.53). The macro-bending loss at 20 mm$\phi$ decreases significantly by increasing $d/A$, while maintaining the same $A_{\text{eff}}$. However, the ESM property can not be kept, when $d/A$ is larger than 0.43, as described before.

Next, we show the numerical relationship between macro-bending losses at 20 mm$\phi$ and $A_{\text{eff}}$ at 1550 nm, in the case of step-index SMFs, in Fig. 7. Here, the well-known structural parameters, namely core diameter (2a) and relative refractive index difference ($\Lambda$), were adjusted to keep the $\lambda_c$ at 1530 nm for any values of $A_{\text{eff}}$. Interestingly, the
result of the PCF with \( d/\Lambda = 0.43 \), which gives the ESM property, shows the almost the same tendency as that of the SMF with \( \lambda_c \) of 1530 nm, which should give fair comparisons each other.

Based on these results, we fabricated the PCF with \( d/\Lambda = 0.43 \) and \( A_{\text{eff}} \) of about 150 \( \mu m^2 \), as well as the SMFs with \( A_{\text{eff}} \) of about 115 \( \mu m^2 \) and 130 \( \mu m^2 \). Then, we compared the micro-bending loss properties between the PCF and the SMFs, keeping the same fiber diameters of 186 \( \mu m \) and the same coating diameters for the fair comparison. We summarize the obtained properties of the PCF and the SMFs in Table 3. As shown in Table 3, the experimental results showed good agreements with the calculated ones.

Figure 8 shows the micro-bending loss spectrum of the PCF and the SMFs. The red curve corresponds to the PCF with \( d/\Lambda = 0.43 \) and \( A_{\text{eff}} \) of 150 \( \mu m^2 \). The blue and green curves correspond to the SMFs with \( A_{\text{eff}} \) of 115 \( \mu m^2 \) and 130 \( \mu m^2 \), respectively. In order to obtain the micro-bending loss spectrum, we measured the difference of losses between spooling condition on a bobbin with sandpaper (#1000) and loose condition. As shown in Fig. 8, the micro-bending loss of the PCF with \( A_{\text{eff}} \) of 150 \( \mu m^2 \) is lower than that of the SMF with \( A_{\text{eff}} \) of 130 \( \mu m^2 \). In the telecom band, the micro-bending loss of the PCF with \( A_{\text{eff}} \) of 150 \( \mu m^2 \) is similar to that of the SMF with \( A_{\text{eff}} \) of 115 \( \mu m^2 \). It indicates that the air holes in the cladding seem to have some effects to prevent the micro-deformation around the core. The obtained results demonstrate the new possibility of PCFs to realize even larger \( A_{\text{eff}} \) than those of conventional solid fibers. A potential problem of the large-\( A_{\text{eff}} \) PCFs are micro-bending loss increase towards short wavelengths, because the mode gap between the guided core mode and leaky cladding mode decreases towards short wavelengths, in contrast to the conventional solid fibers. Actually, the micro-bending loss in wavelengths shorter than 1450 nm is larger, which limits the usage of short wavelength bands e.g. 1.0-\( \mu m \) band, in the case of large-\( A_{\text{eff}} \) PCFs.

3. Photonic Crystal Multi-Core Fibers (PC-MCFs)

3.1 Further Improvements by Using Multi-Core Fibers

The transmission lines realized by PCFs have large potentials, as described in the previous section. Other breakthrough, which has been paid considerable attention, is multi-core fibers (MCFs) to realize space division multiplexing (SDM) transmission. Of course, photonic crystal multi-core fibers (PC-MCFs), where each core can realize ultra wide-band transmission or larger \( A_{\text{eff}} \), have a potential for the ultimate high-capacity transmission [10]. An image of increasing the capacity is summarized in Fig. 9.

As indicated in the figure, the multi-core technology can offer another possibility of increasing the transmission capacity drastically by SDM. Here, we described the quantitative analyses to demonstrate some merits of using PC-MCFs at first. Then, we show an example of R&D on ultra wide-band PC-MCFs.

3.2 Comparisons of PC-MCFs and Solid MCFs in Terms of Large \( A_{\text{eff}} \) and High Core-Density

At first, the properties of PC-MCFs and solid MCFs are compared by the FEM simulation. For a fair comparison, the macro-bending loss conditions for solid fibers and PCFs are set to be the same, which is 5 dB/m at 20 mm\( \phi \). Since the macro-bending losses increase towards short wavelengths in the case of PCFs, we set the wavelength for the bending loss calculation to be at \( \lambda_c \) for PCFs, and at 1550 nm for solid fibers. We simulated \( A_{\text{eff}} \) and core pitch of 7-core solid fibers and PCFs having \( \lambda_c \) of 500 nm, 850 nm, 1000 nm,
1310 nm, and 1550 nm. The core pitch is a very important factor to determine the required core numbers in a unit area. For this simulation, the required core pitch was defined as a value, where cross-talk between neighboring cores becomes −30 dB after 100 km transmission. In the reference [24], it is said the Mode Path Interference (MPI) of −22 dB yields roughly 1-dB BER penalty. Considering the central core receives a crosstalk from the 6 cores, we believe the crosstalk should be suppressed to less than −30 dB. Needless to say, determining the adapted crosstalk for the real systems will require some system simulations or experiments in the future. The obtained results are summarized in Fig. 10. As shown in Fig. 10, PC-MCFs can show the larger $A_{\text{eff}}$ and smaller core pitch, or higher core density, while keeping the same $\lambda_c$ and the same macro-bending loss. In particular, PC-MCFs with short $\lambda_c$ show drastic improvements, in terms of the core density.

3.3 Design Optimization of PC-MCFs for Ultra Wide-Band SDM Transmissions

As described in the previous section, PC-MCFs showed improved properties, in particular for the cases of short $\lambda_c$. Therefore, we have fabricated the 7-core PCFs with $\lambda_c$ of 500 nm and confirmed the optical properties.

The design optimizations of the 7-core PCFs will be explained firstly. The structure of 7-core PCF is shown in Fig. 11, where $d$, $\Lambda$ and ring number indicate same factors as 1-core PCFs and the core intervals indicate the pitch numbers between the neighboring cores.

First of all, to realize the long-distance SDM transmission, it is essential to propagate the light through each core individually. To estimate the interferences between cores, we calculated a coupling length of the 7-core PCFs. The coupling length is defined as the length, where 100% of the optical power of one core transfers to another core. If the transmission distance is much shorter than the coupling length, the interference between the cores can be ignored. Therefore, we defined the transmission distance as 1/100 of the coupling length and examined the relation against the core intervals. Here, the $d/\Lambda$ was set to be 0.43, where the strict ESM could be realized as described before, and the results in the case of $\Lambda$ of 5, 7, 9 $\mu$m were compared as shown in Fig. 12. From the simulation, it was found that it would be possible to extend the transmission distance over 100 km by enlarging the core intervals to more than 9 layers. The coupling length was calculated at 1550 nm, and since the electrical fields have a wavelength-dependence, the coupling length also has the wavelength-dependence. However, the wavelength-dependence of the coupling length is not very large, since that of electrical fields is not so steep.

Secondly, ring numbers at the outer region of the cores need to be optimized to suppress the confinement loss. Simulation results revealed that at least 5 layers were required to suppress the confinement loss to $<0.01$ dB/km at 1550 nm, when the $d/\Lambda$ was 0.43. Last but not least, each core needs to be optimized to realize the wide band transmission characteristics for the ultra large capacity transmission. The bandwidth of the short wavelength region is limited by the macro-bending loss. In spite of the limit, an ultra wide band transmission from 500 nm (visible region) to 1700 nm could be realized with low macro-bending loss in the case of $\Lambda = 5 \mu$m. From these results, it was revealed that the 7-core PCF with $d/\Lambda = 0.43$, $\Lambda = 5 \mu$m, core interval = 10 layers and outer ring number = 5 layers could realize the transmission over 100 km in the wide-band transmission region over...
Fig. 13  The obtained structure of the 7-core PCF.

Table 4  Optical properties of each core at 1550 nm.

<table>
<thead>
<tr>
<th>Core</th>
<th>Dispersion</th>
<th>D. Slope</th>
<th>$A_{eff}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>40.0</td>
<td>0.071</td>
<td>55.5</td>
</tr>
<tr>
<td>Core A</td>
<td>41.2</td>
<td>0.072</td>
<td>38.7</td>
</tr>
<tr>
<td>Core B</td>
<td>40.2</td>
<td>0.071</td>
<td>41.8</td>
</tr>
</tbody>
</table>

500–1700 nm.

3.4 Fabrication Trials of a PC-MCF for Ultra Wide-Band SDM Transmissions

To confirm the optical properties of the PC-MCFs, a 7-core PCF was actually fabricated. The sample length was 1 km and the cross-section of the fabricated 7-core PCF is shown in Fig. 13. A uniform and desirable structure could be obtained from the optimized fabrication process.

The optical properties, measured at the center core (core A) and one of the outer cores (core B) as well as a simulation result, are shown in Table 4. Almost the same properties as the simulation results were confirmed. There were almost no discrepancies between the properties of core A and B and no influence of the confinement loss was observed. As shown in Fig. 14, low macro-bending losses were confirmed in the wavelength region above 500 nm, so this fiber was confirmed to be applicable for the ultra wide band transmission. A cross-talk of the two cores after 1 km transmission, measured by the set-up shown in Fig. 15, was less than $-60 \text{ dB}$, so we could expect a cross-talk of $<-35 \text{ dB}$ would be obtained after 100 km transmission. This value matches the simulation results and is low enough for practical applications. As described, some transmission simulations and experiments will be required to confirm that this value will truly be applicable for the real field deployment.

In addition, some reports indicated that the macro-bending losses affect the cross-talk properties, which need to be addressed in the future [25], [26]. However, we believe the fabricated 7-core PCF is quite attractive in terms of potentials to realize long-haul, ultra wide-band, 7-core multiplexing, high-capacity transmission.

4. Conclusion

We have investigated the merits of using PCFs for the aspect of ultra wide-band transmission and the realization of large $A_{eff}$. We also analyzed the merits of PC-MCFs over solid MCFs for future high-capacity transmission. A 7-core PCF, having ultra wide-band transmission ability, was fabricated to confirm the merit of PC-MCFs.

References


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